NAVIGATION CANALS IN INDIA.

TWO LECTURES

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LECTURE I.

GENTLEMEN—

I SHALL endeavour to briefly lay before you those points connected with the design and construction of navigation works in India which, after an experience of about a quarter of a century, seem to me to be of the greatest importance, and which, as far as I am aware, are not treated of in any published work.

The navigation canals hitherto constructed in India may be divided into two classes,—the first, generally called "High Level," intended primarily for irrigation purposes, also provided with locks so as to be available for traffic. They taking off from a river, as a rule immediately above a weir constructed across it, either run down a ridge roughly parallel to the river, or in a direction more or less at right angles to it, follow a contour line until they meet and fall into another stream and so connect two systems of navigation.

The second class described as "Tidal" are cuts connecting rivers flowing through the alluvial plains within tidal influence. They are either open cuts, or they are locked at their entrances.

Of the first class are the Sone and Orissa Canal systems and the Midnapore Canal in its upper reaches. Of the second class are the reaches of the Midnapore Canal between the Rupnarain and Damuda rivers, and the latter and the Hooghly, the Hidgellee and Orissa Coast Canals, and the Calcutta and Eastern Canals.

It is my impression that few, if any, high level navigable canals will be again constructed in Bengal where, for purposes of communication, they certainly cannot, either in economy or efficiency, compete with railways; and, even if new irrigation works are undertaken, it is doubtful whether they will be adapted for navigation also.

On the other hand, I think it likely that a considerable number of tidal canals will be made connecting some of the innumerable creeks traversing the Gangetic delta, improving the water communications of a large area through which the construction of railways would be very costly. I will therefore in this lecture devote myself to the consideration of tidal canals, as they are those with which there is the greatest likelihood of your having to do hereafter, and also because their successful construction, from a financial point of view, entirely depends on a clear understanding of the principles on which they should be designed. In the case of high level canals, they are primarily intended for irrigation purposes, and become navigable merely by the addition of a lock at their heads and at each over-fall.

If there was no silt suspended in the water of tidal rivers, the making of open cuts connecting them would be simple and cheap; but unfortunately these waters are so heavily charged with solid matter that such an open cut, unless under very exceptional circumstances, quickly deteriorates by the deposit in it of silt involving frequent closings for re-excavation, which is not only a most costly operation, but much interferes with the efficiency of the channel for purposes of navigation.

It is evident that if a cut be made between two tidal rivers there will be a flow through the cut from the river in which the water surface stands at the highest level; so if two rivers were so connected with a considerable difference in the time of high water at the connected points, and a similar tidal range at these points, there would be a flow in one direction during flood and the other during ebb, with but a very short period of slack water, and such a cut would not be liable (or only to a minor degree) to deterioration from silt.

Unfortunately such conditions do not, as a rule, obtain, as it is generally required to connect the two rivers at points equally distant from the sea with approximately the same hour of high water and range of tide, with the result

that the tides through the cut from either end meet, causing slack water and an inevitable deposit of silt. Such is the case with the Bhangore khal, a portion of the eastern canal system which connects the Biddiadharee and the Koolte-gong rivers. The tides from either end meet, and within a short time of the silt being cleared, the channel is again deteriorated so as to be impassable for all but boats of very light draft. After many years of suffering from this cause the Bhangore khal is about to be provided with locks. Tolly's Nala connecting the Hooghly with the Biddiadharee keeps open better owing to the different tidal range in the two rivers, but slack water is experienced at a point near Russa Pugla with the result that a bar forms, and, however frequently removed, it quickly grows again to a certain level, above which, however, it does not rise.

It will thus be seen that, in order to render a canal connecting two tidal rivers entirely satisfactory for navigation, it is necessary that it should be locked at either end.

In the locked tidal canals earliest constructed in Bengal, the water was taken into them through the locks, the gates opening when the water in the river rose higher than that in the canal, and closing of themselves when the tide in the river again fell below the canal level, thus impounding the water in the canal. It is evident that each tide which rose higher than the canal level would open the gates and raise the level more or less. The canal level then falls as water is expended by lockage, leakage and evaporation, until another tide rises above it and again opens the lock gates. Practically the canal level can never fall much below high water in the river on the day of lowest neap tide, and in a canal of considerable length where the surface area is large, its level never falls so low as high water of neaps.

The method of filling a tidal canal through the locks has the disadvantage that the suspended silt in the water is deposited in the canal within the first mile or two from the lock causing an obstruction which can only be removed either by dredging or by closing the canal to traffic and dewatering it to admit of excavation by hand. In order to get over this difficulty the several reaches of the Orissa Coast Canal have been constructed, so that the supply water shall be admitted through a sluice instead of the lock, which sluice is connected with the navigable canal by a channel about two miles in length, in which channel all the silt deposits and only clear water enters the navigable channel.

The latest improvement is to have the channel between the sluice and the canal double, so that one may be closed for silt clearing while the other is in use.

It will sometimes happen that a natural creek will exist and be so situated relatively to the canal that by sluicing its mouth it can be utilised as a supply channel, and it may be of such large section that for many years it will receive the silt deposited without any clearance being required. On the ranges of the Orissa Coast Canal several such creeks were utilised with most happy results. When a canal has a supply sluice it is necessary that provision be made to prevent the tide entering through the locks. This is most successfully done by providing the locks with reverse gates on the river side, but as a makeshift the gates may be held closed against a head by strut gates, which when not in use lie in the gate recesses. On the Orissa Coast Canal there are reverse gates on the river side and the inner canal side gates are fitted with struts. This arrangement allows of the lock being worked when the river is at a higher level than the canal, but I should recommend that each lock be fitted with two pairs of reverse gates for the more easy passing of traffic at such times.

Having described the nature of a locked tidal canal, I shall now explain how you should proceed if you had one to design.

Suppose two tidal rivers, 20 miles apart, are to be connected by a canal, the following data will be required :—

1. A longitudinal section on the line of the proposed canal. (*N.B.*—It will generally be found within tidal range that the country is a dead level and below high water of spring tides.)
2. Tidal guage readings for as long a period as possible in each river.

It has then to be determined what the dimensions of lock chambers are to be, the level of their sills, the width and level of canal bed, and finally the

sectional area of vents to be allowed to the supply sluice, and the dimensions of channel between the sluice and the canal.

With regard to locks, the chambers differ in dimensions on the several systems of canals in Bengal. Those on the Midnapore, Hidgellee, and Coast Canals are 150 feet long by 20 feet wide; on the Orissa Canal system 120 by 17; and in the locks at Chitpore and Dhappa on the Calcutta Canal the gates are 40 feet in width, and in addition to the usual lock chamber there is a basin capable of containing a large number of boats at one time.

The dimensions of future locks should be the same as those of the system with which they will be the most intimately connected, but I consider that 150 by 20 is the best to adopt if there are no local reasons to the contrary. However, in my opinion much might hereafter be done by District Boards in the way of local water communication, where the locks would be of a very small size, say 50 or 60 feet long and 8 or 10 feet wide.

It has been usual to place the lower sills of tidal locks not less than 3 or 4 feet below lowest low water, so that they may be passed at almost all times. I think, however, that when designing a tidal navigation canal, it might be considered whether locks would not suffice with the sills so placed as to give, say, 5 feet depth over them at half tide. This would mean the raising of the sills 5 or 6 feet above the levels of those hitherto constructed and would very largely reduce the cost of building the lock.

In existing locks it is found practically impossible to keep the entrance between the lock and the river cleared of silt to the sill level, so the sills might just as well have been not so deeply placed. A delay of a few hours at a lock waiting for the tide does not very much matter to the class of traffic chiefly using canals: if once within it, it secures a good channel free from obstruction. The form that tidal canals will take in the future will, in my opinion, be the canalisation of existing tidal creeks by locking and sluicing them, and the cheaper that such locking sufficient for the purpose can be effected the better chance will there be of raising the money required, and of an adequate return for the expenditure being obtained.

With regard to the depth and width of the canal I would advise its being designed so as to have a depth, when the surface is at the lowest level, of not less than 7 feet, which depth will accommodate almost any of the boats plying on the Bengal rivers, and be also sufficient for passenger steamers to run in. As to width, experience shows that 40 feet at bed level will allow of a large traffic, but a width of 60 feet is better if funds are available, and this is the width which I shall assume in the following calculations.

Supposing the surface level is subject to a variation of 2 feet, then the mean depth would be 8 feet, and if the bottom width be 60 feet and the ratio of slopes 2 to 1, the mean surface width will be 92 feet and the mean sectional area 608 superficial feet. We now come to the calculation of the level to which the canal may be expected to fill through the supply sluice, and the dimensions of the latter.

The levels to which the tides rise vary much throughout the year both from day to day and from month to month. They are highest about the time of new and full moon, gradually falling and rising again between those periods, so that we have in each lunar month two maxima and two minima high water levels. The levels also differ in different months of the year, being for the rivers of the Gangetic delta lowest in December and January and highest in August and September, in which months they are swollen by the enormous quantities of water coming down the Ganges.

There is another peculiarity about the tides which bears on the filling of a tidal canal, viz., the fact that in December, or the month of lowest tides, the night tide rises about 2 feet higher than the day tide, so that the canal level raised by the former will be above the latter, and for supply purposes we have only one tide in the 24 hours. From January the respective levels of the day and night tides gradually assimilate, and then the day tides become the higher, until in June they are as much above the night tides as the latter were above than the day ones in December.

The December and January tides being the lowest of the year, it is evident that the minimum level for the canal must be calculated from them, and that for the rest of the year we shall be certain to get sufficient water.

Diagram No. 1 shows for Diamond Harbour the levels of high and low water for the night tide of two periods of the lowest spring tides of the year and the intermediate neaps. You see from the diagram that the tide after rising for four days at the time of new moon to about 16 feet above zero, the high-water level falls day by day until it only reaches to about 12 above zero, when it again gradually rises until at full moon and for a few days afterwards it attains to its former level.

The second diagram shows the curve for one of the highest tides.

We now come to calculating the canal level and the dimensions of the supply sluice. When I was constructing the Orissa Coast Canal and supply sluices had to be designed, I found that there was no known formula which would enable me to calculate the sectional area of vents necessary for the sluice in order that with a certain rise of tide the canal should be filled to a certain level. The known laws of hydraulics did not suffice for the solution of the problem. I consequently undertook a series of experiments on the existing Hidgellee Tidal Canal which filled through the locks, and obtained data for an empirical formula which enables the problem to be practically solved. My note on the matter was approved by Professor Unwin and was published by the Institute of Civil Engineers. You will find it in Volume LXXVIII of the Transactions Sessions, 1883-84. Mr. G. C. Maconchy, then my Assistant (now Under-Secretary, Bengal Public Works Department), with the use of some of the data obtained by my experiments, worked out a rigorous mathematical solution which was pronounced to be sound by Professor Unwin and is published by the Institute as an Appendix to my paper. I commend it to those amongst you who have the higher mathematics. I have not now time to go through the details of my experiments, but will proceed to show you how to use the result arrived at.

The formula established was—

$$f=\frac{3\,an\,k \times S\sqrt{h}}{8\,A}$$

Where—

f=the rise in the canal level due to one tide.
a=sectional area of one vent of the supply sluice.
n=number of vents.
k=the coefficient in the formula $V=K\sqrt{h}$ for velocity through a sluice. (It may vary from the maximum 8 to the minimum 5.)
h=the rise of the tide in river above the canal level.
S=the number of seconds corresponding to h that the river was above the canal.
A=the area of the canal surface.

The theoretically perfectly designed sluice is one which will, during a period of spring tides, raise the canal level through the same height as it had fallen since the previous spring tides. A smaller sluice would be insufficient and a larger one would be superfluous.

The canal that we are considering has a mean width at surface of 92 feet, and it is 20 miles long; the area of its mean surface (or A of the formula) will consequently be 9,700,000 superficial feet. The sectional area of one vent of the sluice we will take at 22·5 superficial feet (which in practice is found to be a suitable size), and I will show you that if we take the number of vents at 11 we obtain the theoretically perfect sluice. The value for the coefficient k which I shall use is 7, which experience has led me to believe to be that obtaining with vents of large area under small heads. In designing the Coast Canal sluices, I used the coefficient 5, with the result that more than a sufficient number of vents were allowed to each sluice.

For the determination of S, or the number of seconds that that the tide in the river will be above the canal level, the curve of spring tide must be considered. In the diagram No. 2 I have shown the rise and fall for one of the high tides given in diagram No. 1, and I have also shown on the diagram the upper 2 feet of rise and fall on an enlarged scale, five times that of the curve of the whole tide. From this large scale curve the times can be scaled off. You see that 2 feet from the top the hour line indicates a small fraction above three hours; one foot, two hours and so on. The seconds corresponding to each rise have been taken off and entered in the table below for each

tenth of a foot of rise and in the third column the values of $S\sqrt{h}$ have been entered.

h	S	$S\sqrt{h}$	h	S	$S\sqrt{h}$
1	2	3	1	2	3
0·1	1,800	558	1·1	7,740	8,127
0·2	2,592	1,158	1·2	8,280	9,108
0 3	3,420	1,846	1·3	8,640	9,874
0·4	4,140	2,608	1·4	9,000	10,800
0·5	4,800	3,360	1·5	9,360	11,420
0·6	5,400	4,158	1·6	9,720	12,344
0·7	5,940	4,989	1·7	10,080	13,102
0·8	6,480	5,832	1·8	10,448	13,930
0·9	6,840	6,498	1·9	10,620	14,655
0·1	7,380	7,380	2·0	11,000	15,510

I have learned by actual experience that with a sufficiently large sluice the canal level will rise during spring tides to within about half a foot of the highest rise of tide, which in the present case being 16·00 above datum, the maximum canal level may be taken at 15·5, and if the variation of level be 2 feet, the mean canal level will be 14·5. But the mean between high and low water in the river is 9·00, and consequently the canal water will on an average be 5·5 feet above the tide in the river.

We can now proceed to estimate the daily lowering of the canal level due to expenditure of water.

There are three sources of waste,—*first*, lockage due to boats being passed in and out when the river level is below that of the canal.

If we assume that there will be 40 lockages at either end of the canal in the 24 hours made at all states of the tide, then the whole expenditure of water for lockage will be 80 times the superficial area of the lock chambers multiplied by the mean difference between canal and river levels, or

$$80 \times 150 \times 20 \times 5{\cdot}5 = 1{,}320{,}000 \text{ cubic feet.}$$

The *second* source of waste is the leakage through the lock gates and valves, and through the supply sluice valves, and experience shows that this may be taken at about 2 cubic feet per second from each lock or sluice. We therefore have a total of 6 cubic feet per second for the two locks and the sluice, or

$$3{,}600 \times 24 \times 6 = 518{,}400 \text{ cubic feet}$$

for the 24 hours.

The *third* source of waste is evaporation, which may be taken as a maximum of 0·014 of a foot over the canal surface. We now have

			C. ft.
Lockage	=	...	1,320,000
Leakage	=	...	518,000
	Total	...	1,838,000

but the mean area of the canal surface has been determined to be 9,700,000 superficial feet, which, divided into the loss due to lockage and leakage, gives a daily lowering of

Surface	=	...	0·189
Evaporation	=	...	0·014
	Total	...	·203

For further purposes of calculation we will take the daily lowering at 0·2 of a foot. Let us now return to diagram No. 1. We assume that by the third day of the moon the canal surface will have been raised to the level of 15·5. On the fourth day the tide only just reaches to the canal level, therefore there is no filling done, but the canal falls 0·2, and so it continues to do for the next

nine days during which the tide never reaches it. The canal level by the close of the thirteenth day of the moon will consequently have fallen from 15·5 to 13·5, but on the fourteenth the tide again rises above the canal, and filling is resumed. The rise of the tide on the fourteenth is 14·1, or 0·6 above the canal, and we can calculate the rise in the surface from the formula already given—

$$f = \frac{3\,a n k \times S\sqrt{h}}{8A}$$

$$a = 22{\cdot}5$$
$$n = 11$$
$$k = {\cdot}7$$
$$A = 9{,}700{,}000$$
$$f = \frac{S\sqrt{h}}{14{,}400}$$

From the table on the preceding page it is seen that the value of $S\sqrt{h}$ corresponding to $h = 0{\cdot}6$ is 4,158, which divided by 14,400 gives—

$$f = 0{\cdot}27.$$

The canal will consequently be raised from 13·50 to 13·77, but will again lower 0·2 before the tide of the following day reaches it, at which time its level will be 13·57. The tide of the fifteenth day of the moon rises to 15·00, or 1·43 above the canal, which it will cause to rise 0·74, to again fall 0·2 and so on for each day of the high tides.

In the following table the rise of the canal for each day is worked out:—

Age of moon.	Rise of tide.	Level of canal before filling.	Rise of tide above canal (h).	Rise of canal ( ).	Level of canal after filling.	Daily lowering of canal.
1	2	3	4	5	6	7
14	14·1	13·5	·60	·27	13·77	0·2
15	15·0	13·57	1·43	·74	14·31	0·2
16	15·4	14·14	1·36	·68	14·79	0.2
Full moon	15·8	14·59	1·21	·61	15·20	0·2
18	16·0	15·00	1·00	·49	15·49	0·2
19	16·0	15·29	0·71	·34	15·63	0·2
20	16·0	15·43	0·57	·25	15·68	0·2
21	16·0	15·48	0·52	·22	15·70	0·2
22	15·4	15·50	...	...	...	...

It is seen from this table that by the twenty-second day of the moon the canal level after the daily lowering would be at 15·50, or the same level at which the previous springs left it. The tide of the twenty-second would not reach it, and the canal would lower at the rate of 0·2 a day until again raised by the ensuing spring tide. It is therefore shown that the number of vents required is 11.

I must warn you that the empirical formula we have been using being based on experimental data will only give correct results for conditions approximately the same as those under which the data were obtained. In the observations taken of the rate of filling of the Hidgellee Canal through the lock the sectional area of the waterway through the lock was about ⅓rd that of the canal filled. If therefore the ratio of the sluice ventage and the cross-section of the canal varied very much from 1 to 3, correct results would not be obtained from the formula. In the canal under discussion the ratio of the sluice waterway to the cross-section of the canal is 1 to 2½. I should say that between the ratios 1 to 2 and 1 to 4 sufficiently correct results will be given by the formula.

We can now calculate the dimensions of the channel between the sluice and the canal to ensure the silt suspended in the supply water being deposited in it.

It has been found that the water entering a canal through the sluice drives before it that already in the canal, taking the latter's place, and that practically there is no admixture of the clear water already in the canal and the silt laden taken in from the river. The latter occupies the portion of the channel nearest the sluice until again displaced by that entering on the following day. It is

also found that the interval of one day that the water lies still after entering the canal is sufficient for the deposit of the silt suspended in it.

If, therefore, the channel between the sluice and canal has a capacity sufficient to hold the maximum quantity of water taken in during one tide, then it will answer the purpose of a silt trap.

Referring to the table showing the daily rise during filling, we find that on the fifteenth day of the moon the canal surface was raised from 13·57 to 14·31, equivalent to 7,178,000 cubic feet of water, or to the cubic contents of a length of 10,600 feet of a channel of the same section as the canal with its surface at the level of 14·31. To provide for all the silt being caught in the sluice channel, it would therefore be necessary to have it at least 10,600 feet long, or, say, two miles, to which it would be well to add another half mile to allow for the deterioration of the channel as the silt deposits in it. As already stated, it is desirable that the supply channel should be double, so that one may be in use while the other is closed for silt clearance.

If a channel $2\frac{1}{2}$ miles in length is introduced between the canal and the sluice, the surface area of the canal would be increased from 9,700,000 to 11,000,000 superficial feet, which would somewhat affect the rate of rise and fall of the surface, but the effect would be small and may be neglected.

The following corollaries follow from what has been demonstrated about a tidal canal :—

The expenditure of water is practically independent of the length of the canal.

The daily rate of falling between spring tides and raising of surface during them is inversely as the length of the canal.

The greater the surface area of the canal the less are the fluctuations in its water level, and consequently the level of bed in a long canal may be higher than in a short one, and yet secure the same minimum depth of water.

We have seen that a canal 20 miles long will not fall to a lower level than 13·5, but suppose it is only four miles in length, then its daily rate of lowering instead of being ·2 will be five times as great or one foot, but this is twice as much as the daily fall of the level of high water between spring and neap tides, and consequently in a very short canal the water level will daily fall below that of the succeeding tide which will again replenish the canal. However, as the canal level falls with the waning tides, the expenditure of water for lockage and leakage decreases as the difference of level between canal surface and mean tide diminishes from 5·5 to 2 feet, which diminishes lockage in a like ratio, and leakage as the ratio of the square roots of 5·5 and 2. The total daily expenditure of water will be about half at the time of lowest neaps what it was at the time of highest springs, giving a daily lowering of a canal 4 miles in length of about half a foot.

The formula, I regret to say, does not accurately give the rise of tide above canal level necessary to raise a 4-mile canal through half a foot, as such a short canal is beyond its limits as it was deduced from experiments made on a canal 17 miles in length. However, I have found by experience that a very short canal may fall as low as ·75 below high water of the lowest neap, which in the present case would give the minimum water level to be 11·5 or 2·0 lower than that for a canal 20 miles in length. This would of course necessitate the bed level being also 2 feet lower, which would add largely to the cost of the excavation. Remember that a lowering of the bed by 2 feet means 2 feet of additional excavation at the ground and not at the bed level. If the ground level be 14·00 above datum and the depth 7 feet, with a maximum surface level of 11·50, the width of cutting at surface would be about 100 feet against 60 feet at bed.

It is clear that the greater the surface area of a canal the better, and the advantage is great if a natural channel of large size can be made to do duty for a supply channel, as it not only saves the cost of the latter, but increases the water surface of the canal.

On the Orissa Coast Canal the difficulties of a very short reach were got over by connecting it with a long reach on the other side of the river by means of a jointed iron pipe 3 feet internal diameter laid on the bed of the river.

In my next and last lecture, I shall deal with the silt question, the bearing power of alluvial soil and the designing of locks and supply sluices.

LECTURE II.

On the last occasion that I had the pleasure of addressing you, I discussed the method of supplying a tidal canal with water and the quantity daily expended. We will to-day consider the quality of this water with regard to the silt which, when flowing in the river, it carries suspended in it.

Great as is the importance of knowing all about the silt carried by rivers, there have been fewer experiments made to determine it than we could wish. The only ones I am aware of, and which I shall refer to in this lecture, are the following:—

1. Experiments made in 1842 by Mr. Henry Piddington, Curator, Museum, Economic Geology, on the quantity of silt held in suspension by the waters of the Hooghly at Calcutta in each month of the year. The experiments are recorded in Volume XXIII of the Journal of the Asiatic Society of Bengal.
2. Experiments made by the late Mr. J. C. Vertannes, then Executive Engineer, Public Works Department, Irrigation Branch, when he was getting up the project for the Orissa Coast Canal in 1875, to determine the proportion of silt in the rivers from which the canal was to be supplied.
3. Further experiments made by me in 1885 on the waters of the same rivers when constructing the Orissa Coast Canal.
4. Experiments made under my direction by Mr. P. W. Soutter, Resident Engineer, Kidderpore Dock works, in 1889, to determine the proportion of silt in the water of Tolly's Nala, from which the supply for the Docks is derived.
5. Experiments made in 1893 by Mr. C. E. Livesay, then Executive Engineer of the Nadia Rivers Division, on the water of the Bhageratti.
6. Determination of silt contained in the water of the Hooghly at Pulta, above Barrackpore, where it is drawn from the river for the Calcutta Water-works.

When I was constructing the Orissa Coast Canal, I found that there was a marked discrepancy between the proportion of silt found by Mr. Vertannes ten years previously in the water of the Rusulpur river, and what we were then experiencing in the shape of deposits in the second range of the Hidgellee Tidal Canal fed from that river. I then undertook a series of experiments on the waters of the twelve rivers from which the several ranges of the Hidgellee and Coast Canals are supplied. These experiments, though by no means as extensive as I should have wished, still afford a good deal of information, and the results are instructive in themselves and in comparison with those earlier obtained by Mr. Vertannes.

I shall first describe the method of conducting such experiments which I found by experience to answer best, so that if at a future time some of you may have to ascertain the quantity of silt in water, you may know how to set about doing so.

First of all, you have to obtain specimens of the water, and you may require to take them either from the surface or from certain depths below it. I found that on the whole the simplest and best way was to submerge a narrow-mouthed bottle in the water, mouth uppermost, which gradually filled as the air bubbled out. Common whisky or beer bottles do as well as any. Such a bottle holds 26 ounces, and 16 ounces is a convenient quantity to operate on. If the specimen is to be taken from a certain depth below the surface, it is obtained by fastening the bottle to a pole and sinking it to the required depth. The time occupied in sinking the bottle is only a fraction of that required for it to fill, so the error caused by partial filling before it reaches the full depth is inappreciable. If the depth is considerable, this error

may be reduced by partly stopping up the mouth of the bottle and so increasing the time required for it to fill.

As soon as bubbles cease to come to the surface you know that the bottle is full, and draw it up again and immediately pour its contents into another bottle which you securely cork. This bottle should have an index number on it, against which number in your note book you give particulars of the specimen. You can quite understand that the merely obtaining a number of specimens of water is a laborious process occupying considerable time. Another method by which an average sample for 5 feet from the surface is obtained is to have a tube of that length with a valve at the bottom, opening upwards, which being dropped vertically to the depth of 5 feet and again lifted brings up an average sample of the upper stratum.

You then take home your bottles of water and proceed to estimate the silt in the following manner:—

Place a small glass vessel (those known as beakers are the most convenient) on a pair of scales and exactly counterbalance it, then place 1lb. weight opposite it in the balance. Take a specimen bottle and thoroughly shake it up and pour from it into the beaker water to balance the 1lb. weight. Having so weighed out all your specimens into beakers (each with a number on it), place them in a row and add to each a very few drops of a solution of alum which will cause the silt to quickly settle to the bottom of the beaker. You had best let the beakers stand until next day when you will find the silt settled to the bottoms and the water above it quite clear. Pour off the clear water from each, being very careful to stop as soon as ever the silt in the bottom begins to move. You then collect the silt from each on a filter of blotting paper, and be careful before commencing to do so to pencil the index number on the filter paper. You easily get all the silt into the filter by stirrring it up with the small quantity of water left in the beaker and washing out the last traces with a washing bottle. As soon as the deposits are collected on the filter paper leave them to dry in the funnels until the following day, when carefully remove each filter paper (taking care not be break it and so let any of the deposit escape), and then thoroughly dry at a heat not sufficient to at all char the filter paper. You will find a small kerosine cooking stove with oven most convenient for this purpose. When quite dry very carefully open each filter paper over a large sheet of paper on to which you will let fall its contents, rubbing off by gentle friction all the deposit. The minute trace that will be left adhering to the paper will be a negligable quantity. Now weigh the deposit in an accurate chemical balance. For practical purposes you need not weigh nearer than to one decimal place of a grain. Suppose you find the deposit to weigh 12·5 grains, then this will be the quantity of dry silt in 1 lb. of water. But 1 lb. = 7,000 grains, therefore the proportion by weight of silt to water will be 12·5 : 7,000, or 1 in 560. However, what we want to know for practical purposes is not the proportions by weight, but by volume; that is the number of cubic feet of silt that would be deposited in a canal, for, say, each 100,000 cubic feet of water admitted to it. Silt deposited in a channel when the channel has been dewatered and the silt exposed to the sun until dry enough to be conveniently dug out is what we have mostly to deal with, and by a number of experiments I have found that a cubic foot of silt in a firm state might be taken on the average to weigh 95 lbs., of which 50 lbs. are dry matter and 45 lbs. water. We can with these figures reduce our 12·5 grains of dry silt to the pound of water to cubic feet of damp silt to 100,000 cubic of water. One cubic foot of water weighs 62·5 lbs. If therefore the number of grains of silt found in 1 lb. of water be multiplied by 62·5 × 100,000 and be divided by 7,000 × 50, we obtain the number of cubic feet of damp silt in one lakh of cubic feet of water:

$$\frac{62{\cdot}5 \times 100{,}000}{7{,}000 \times 50} = 17{\cdot}8$$

You have only therefore to multiply the grains of silt found in 1 lb. of water by 17·8 to obtain the number of cubic feet of damp silt in 100,000 cubic feet of water.

In the following table are shown the results of my experiments made in 1885 and a comparison of them with those carried out ten years earlier by

Mr. Vertannes. The latter were recorded by proportions by weight, but for comparison I have reduced all experiments to the same denomination, viz., cubic feet of damp silt to the 100,000 cubic feet of water:—

Results obtained by Mr. Apjohn *in* 1885.

River.	Cubic feet of damp silt (containing 50 lbs. of dry silt and weighing 95 lbs.) per 100,000 cubic feet of river water.								
	When specimen of water was taken.								Mean of all experiments.
	1st spring tides of March—		2nd spring tides of March—		1st spring tides of April—		2nd spring tides of April—	1st spring tides of May—	
	At surface.	Five feet below surface.	At surface.	Five feet below surface.	At surface.	Five feet below surface.	Average sample taken with valved tube five feet long.		
1	2	3	4	5	6	7	8	9	10
Rupnarain at mouth of Gewankhali khal ...	374	...	376	...	130	...	365	...	311
Gewankhali khal in lock entrance	186	...	63	...	128	...	95	...	118
Huldi river	836	...	...	...	...	...	...	1,552	1,194
Russulpore midstream	322	542	3,140	...	1,112	...	...	...	1,280
" near bank at proposed sluice site	172	...	2,176	2,525	3,398	3,710	...	...	2,396
" near old lock entrance	303	641	3,235	5,155	3,362	4,453	...	...	2,858
Goocheda near Bograi lock	19	25	32	34	45	56	113	29	44
Subarnarekha near Jamcoonda lock	64	74	84	98	74	86	116	40	79
Sartha near supply sluice	21	32	75	80	52	57	30	22	46
Panchpara river near lock	50	93	130	305	98	160	...	78	130
Buraballong river at Nulcool midstream ...	33	73	86	128	75	184	...	...	96
" river near bank	...	...	95	121	65	92	...	...	93
Jamka near supply sluice	25	36	38	84	60	74	50	51	52
Kansbans near supply sluice	26	97	50	98	86	111	85	123	84
Metai near Chartbatia	101	...	24	...	33	...	89	101	70

Comparative statement of results obtained by Mr. Vertannes *in August and September* 1875 *and by* Mr. Apjohn *from March to May* 1885.

River.	Number of experiments—		Maximum number of cubic feet silt found in 100,000 cubic feet of water—		Minimum number of cubic feet silt found in 100,000 cubic feet of water—		Mean of all experiments—		Ratio of silt at surface to that at five feet below—	
	By Vertannes.	By Apjohn.	By Vertannes.	By Apjohn.	By Vertannes.	By Apjohn.	By Vertannes.	By Apjohn.	By Vertannes.	By Apjohn.
1	2	3	4	5	6	7	8	9	10	11
Rupnarain	1	4	71	376	71	130	71	311	...	...
Gewankhali lock entrance	1	4	90	186	90	63	90	118	...	...
Huldi	6	2	382	1,552	75	836	103	1,194	1·6	...
Russulpore	8	15	102	5,155	11	172	63	2,283	1·5	1·3
Goocheda	6	8	160	113	35	19	88	44	1·2	1·2
Subarnarekha	5	8	170	116	86	40	129	79	1·3	1·2
Sartha	...	8	...	80	...	21	...	46	...	1·1
Panchpara	8	7	56	305	8	50	21	130	1·4	...
Buraballong	8	10	61	184	9	33	30	94	1·0	1·7
Jamka	...	8	...	84	...	25	...	52	...	1·6
Kansbans	...	8	...	123	...	26	...	84	...	1·7
Metai	...	5	...	101	...	24	...	70	...	...
	43	87	...	...	...	...	...	...	1·3 mean.	1·48 mean.

You will see that the results obtained differ enormously in different rivers, and in the same rivers at different times. The averages obtained by me varied from a minimum of 44 for the Goocheda to 2,858 for the Russulpore.

From the lower table you see that in every case except those of the Subarnarekha and Goocheda rivers, I found more silt than Mr. Vertannes did. What rational explanation can be given of this?

The following is mine, which you can take for what it is worth, but it is the result of much consideration of the subject. Mr. Vertannes made his experiments during the rainy season in the months of August and September, and I made mine during the dry season months of March, April, and May, and yet I found the larger proportion of silt. This is contrary to general experience as rivers carry more silt in their water when swollen by the rains than when at their lowest, but consideration of the nature of the rivers whose waters were experimented on gives, I consider, a plausible explanation. Of the eight rivers which both of us experimented on, all, with the exception of the Subarnarekha and Goocheda (the latter a small branch of the former), are mere tidal creeks draining no considerable area, and what area they do drain is rice land, the water from which flows off quite free from silt and so

dilutes the silt-bearing tidal water, reducing the proportion of solid matter in the latter to less than what is found during the dry season, when the action of the strong tides stirs up the silt originally brought down during floods and deposited in the estuaries. The Subarnarekha being a river with a large drainage area above the alluvial plains carries great quantities of silt when in flood, and proportion is greater at such times than during the dry season.

In the lower parts of the estuary of the Ganges, of which several of these rivers are mere branches, the infinitely finely divided silt brought down by the freshets is deposited, and during the dry season of strong tides it is rolled backwards and forwards. The stronger the tide, the more silt being carried in the water, the proportion being much greater during spring-tides than during neaps, and the quantity increases from the time of low to that of high water. This is clearly shown by experiments made by me in 1885 on the Russulpore river at high water before, during, and after springs; also at certain intervals of time between high and low water. For this purpose specimens were taken at high water on six consecutive days of May, three days before and two days after the highest spring-tide, and on the day of the latter specimens were taken at low water, and at intervals of one hour up to high water, the velocity of the tide at the time of taking the samples being also observed. The results are given in the following table:—

Date.	High-water level above Kidderpore silt.	Cubic feet of silt per 100,000 cubic feet water.
1	2	3
12th May ...	116·11	274
13th „ ...	116·85	474
14th „ ...	117·33	878
15th „ ...	118·53	5,060
16th „ ...	117·46	1,800
17th „ ...	117·33	1,396

Time of observation.	Velocity of current.	Cubic feet of silt per 100,000 cubic feet of water.
1	2	3
Just after flood made	1·9 feet per second	497
After one hour's flood	3·6 ditto ...	618
After two hours' flood	3·5 ditto ...	823
After three hours' flood	2·8 ditto ...	1,777
High water ...	0·0 ditto ...	5,060

You see that on the day of highest rise the proportion of silt was 18 times greater than it had been three days previously and 10 times greater at the time of high water than it was immediately after flood had made.

In the case of this Russulpore river the enormous increase in the proportion of silt found in its water by me compared to that determined by Mr. Vertannes ten years earlier is not to be explained by the different seasons of the year at which the experiments were made, but by the fact that the river had in that period much altered in character. Formerly it used to be of great depth at the place where the canal locks into it, so deep, indeed, that none of the old sections which cross it recorded in the Executive Engineer's Office show the depth, but in consequence of the reclamation of low lying jungle land along its banks, which used formerly to be flooded by high tides, having reduced the tidal scour, the river rapidly silted up until in 1885 it had become almost fordable at low water where formerly it had been so deep, and since then it has

become quite fordable. The very strong tides of the month of May rushing over the mud flats now formed naturally stir up the deposit until the water becomes practically liquid mud. You see that on the 15th of May 1885 the water actually contained 5 per cent. of solid matter.

The Huldi is another river which has changed its character for the worse from the same cause, though not to the same extent as the Russulpore. I found four times greater a proportion of silt in its water than Mr. Vertannes had done ten years earlier, but in that of the Russulpore fifty times. Twenty years ago the Russulpore carried the less silt of the two, and the second range of the Hidgellee Tidal Canal which was first constructed to be filled from the Huldi was altered in 1876, so as to receive its water from the Russulpore, but of late the former source of supply has been reverted to. Compared with the Russulpore and the Huldi, the other rivers whose waters have been experimented on are clear and limpid streams.

In the general abstract of the average proportions of silt in the waters of these rivers which we shall come to further on, I have arrived at the average proportion for the year by taking that determined by Mr. Vertannes to prevail for the four months of the flood season, and that found by me for the remainder of the year.

The experiments made by Mr. Piddington more than half a century ago were 12 in number, he having drawn a specimen of water from the Hooghly at noon on the first day of each month. He was aware that the proportion of silt varied with the state of the tide, but he considered that by taking the samples irrespective of tide at a fixed hour once a month he would eliminate the source of error due to the varying state of the tide, but the number of samples obtained by him was not sufficient to have had such an effect. These results show the largest proportion on the 1st June and the smallest on the 1st October, which is certainly contrary to general experience. Reduced to the denomination that I have adopted, the maxium quantity per 100,000 cubic feet found by him was 340, the minimum 126, and the mean for the year 158. However, there is a feature about Mr. Piddington's determination that largely affects the results obtained. The bottles containing his samples stood for some years before the proportion of solid matter was determined, and in this interval the calcareous matter held in solution while in the river as a bicarbonate crystallized on the insides of the bottles, and of the total average of 8·8 grains of solid matter to the pound of water obtained by him, only 3·8 grains were earthy and 5 grains were carbonate of lime. If, therefore, he had determined the proportion of silt in the way adopted by me, the carbonate of lime would have remained in solution, and in place of the deposit obtained, representing 158 cubic feet of damp silt to the 100,000 cubic feet of water, it would only have represented 75.

Mr. Soutter's experiments on the water of Tolly's Nala were conducted by drawing two samples at the time of high water once a week during the months of May and June for the determination of the hot weather proportion and during July and August for the flood season. The proportions found by him during the dry months varied greatly according to whether the tides were neaps or springs, that for the latter periods in the two months being respectively $9\frac{1}{2}$ and $10\frac{1}{2}$ times what it was for the former. The variation in the flood months was much less, being only $2\frac{1}{4}$ and $3\frac{1}{4}$.

The average quantities of damp silt from 100,000 cubic feet of water found by him were—

May ...	... 58	July ...	... 161
June ...	... 55	June ...	... 173

I have been favoured by Mr. Kimber, Engineer to the Calcutta Corporation, with a return for two years, showing the proportions of silt for each month in the year found in the water when first admitted to the settling tanks of the Calcutta Water-works.

In the following table I compare them with Mr. Piddington's results and those obtained by Mr. Soutter for Tolly's Nala for four months. You will see that the proportions for Tolly's Nala exceed by 27 per cent. those for the Hooghly at Pulta in the same months. The mean proportion for the whole year in Tolly's Nala has been calculated on the assumption that that for the

four months bears the same proportion to that for the whole year as has been found at Pulta :—

Month.	Cubic feet of damp silt to 100,000 cubic feet water.		
	Hooghly by Piddington.	Hooghly at water-works.	Tolly's Nala.
1	2	3	4
January	40	10	...
February	...	13	...
March	106	16	...
April	130	30	...
May	85	33	58
June	260	56	55
July	67	146	161
August	59	118	173
September	68	73	...
October	28	63	...
November	25	64	...
December	32	29	...
Mean for whole year ...	75	54	69

You see that Mr. Piddington's results, though fairly comparable for the whole year with the later experiments, are not so month by month.

It was to be expected that the water-works experiments would show a less proportion of silt than the others, as the water is drawn from the river on the last of the ebb when there is less matter suspended in it than at any other time of tide.

Mr. Livesay's experiments on the water of the Bhagiratti were conducted during the months of August and November. He drew his samples at intervals of 5 feet from the surface to depths of from 15 to 30 feet. I shall return to his experiments presently when discussing the distribution of silt at various depths, but shall only say now that, taking August to represent the flood months and November the dry months, his experiments give a mean for the year for the 5 feet immediately below the surface of 107 cubic feet of silt per lakh of cubic feet of water.

From the following abstract of the several series of experiments which I have now enumerated, I shall omit the Huldi and Russulpore rivers which, as already described, are mere ditches in which strong tides stir up the mud which is deposited and rolled about over and over again :—

Abstract of experiments showing the proportion of earthy matter suspended in the water estimated as cubic feet of damp silt containing 50 *lbs. of dry matter and* 45 *lbs. of water to* 100,000 *cubic feet of water.*

Date and number of experiment.		River at Calcutta.	Experiments.	Cubic feet of silt to 100,000 cubic feet of water.
Date.	No.			
1	2	3	4	5
1842	12	Hooghly ...	Mr. E. Piddington ...	75
1894	79	Do. at Pulta	Calcutta Water-works ...	54
1889	30	Tolly's Nala ...	Mr. P. W. Soutter ...	69
1893	14	Bhagiratti ...	" C. E. Livesay ...	65
1875 and 1885	78	Rupnarain ... Gewankhali Khal Goocheda ... Subarnarekha ... Panchpara ... Burraballong ...	Mr. J. C. Vertannes and Mr. J. H. Apjohn.	118
1885	21	Sartha ... Jamka ... Kansbans ... Metai ...	Mr. J. H. Apjohn ...	62
	234		Mean for all the rivers...	76

It thus appears that neglecting the Huldi and Russulpore rivers, we get as the mean result of 234 experiments that the Bengal rivers in their tidal portions carry a mean for the whole year at or near the surface of 76 parts of silt to 100,000 of water one and one-third cubic inches to one cubic foot.

We now come to the question of whether the experiments made indicate that there is any law according to which the proportion of silt varies with depth from surface. I think I can show you that there is sufficient evidence to justify a strong presumption that there is such a law even if it does not absolutely establish it.

In the last two columns of the first table given, you will see the average results of the experiments made by Mr. Vertannes on six rivers and by me on seven. He found the silt 5 feet below the surface to be in the ratio of 1·33 to 1, and I determined the mean ratio for the seven rivers to be 1·48 to 1. These series of experiments are sufficiently near in their results to establish the fact that there is a greater proportion of silt below than at the surface; but to ascertain whether there is any law of variation, we require experiments in which the samples of water have been simultaneonsly drawn from three or more different levels. The following are the results of experiments made by me in the Buraballong river on three days of March 1885, and one experiment made by Mr. Vertannes in the Russulpore ten years previously:—

Depth.	CUBIC FEET OF SILT PER 100,000 CUBIC FEET OF WATER.				Proportion of silt calculated by adding $\frac{1}{10}$th to that at the surface for each foot of depth below surface.	
	17th March.	30th March.	31st March.	Mean.		
1	2	3	4	5	6	
	Buraballong river midstream.					
Surface	86	75	121	94	94	By Apjohn.
5 feet below ...	128	184	117	143	141	
10 " " ...	150	214	117	160	188	
15 " " ...	171	267	258	232	235	
	Buraballong river near bank.					
Surface	95	65	95	81	81	
5 feet below ...	121	92	176	120	120	
	Russulpore, 14th September 1875.					
Surface	...	...	...	59	59	By Vertannes.
2 feet below ...	...	...	...	75	71	
4 " " ...	...	...	...	78	82	
7 " " ...	...	...	...	102	100	

It is seen from the above that in the first series of experiments the proportion of silt actually found at the several depths closely agree with those calculated by adding $\frac{1}{10}$th for each foot from the surface. In the second series the silt at 5 feet from the surface is exactly determined by the above process; and in case of Mr. Vertannes' old experiment, the quantities of silt calculated and observed at all the depths agree. A law certainly seems to be established that the proportion of silt increases in arithmetical progression for each equal increment of depth from surface. In the above experiments the common difference is one-tenth for each foot, but it is not of course reasonable to suppose that the same rate of difference would obtain in every case. This was the mean rate for all my experiments when the proportion of silt at 5 feet from the surface was 1·48 times greater than at the surface; but though the difference found by Mr. Vertaunes was the same in the one experiment above quoted when he ascertained the proportion at four different depths, yet the mean difference for all his experiments for 5 feet below the surface gave 1·33 as the ratio to that at the surface, or a common difference of 0·066 for each foot or $\frac{2}{3}$rds of that determined by me.

It was with a view to testing this law that Mr. Livesay in 1893 made his experiments on the Bhagiratti, of which the following is an abstract :—

Experiments made by MR. C. G. LIVESAY *on silt distribution in the river Bhagiratti, Murshidabad district.*

RIVER RISING.

Depth from which sample of water was taken.	Date, 1893.	Surface velocity in feet per second.	Cubic feet of damp silt per 100,000 cubic feet of water.	Proportion of silt calculated by adding 7·7 per cent. of that at surface for each foot below surface.
1	2	3	4	5
0	12th August	3·6	114	114
5			162	154
10			195	195
15			260	236
20			276	276
				Proportion of silt calculated by adding 5 per cent. of that at surface for each foot below surface.
0	15th August	3·6	81	81
5			114	104
10			130	128
15			146	151
20			162	175
25			199	199
				Proportion of silt calculated by adding 10 per cent. of that at surface for each foot below surface.
0	20th August	3·5	98	98
5			130	127
10			178	156
15			244	244
				Proportion of silt calculated by adding 10 per cent. of that at surface for each foot below surface.
0	20th August	3·5	98	98
5			146	127
10			162	156
15			244	244

RIVER FALLING.

Depth from which sample of water was taken.	Date, 1893.	Surface velocity in feet per second.	Cubic feet of wet silt per 100,000 cubic feet of water.	Proportion of silt calculated by adding 3·7 per cent. of that at surface for each foot below surface.
1	2	3	4	5
0	1st November	6	117	117
5			153	139
10			176	161
15			188	182
20			211	204
25			223	226
30			247	247

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Depth from which sample of water was taken.	Date, 1893.	Surface velocity in feet per second.	Cubic feet of wet silt per 100,000 cubic feet of water.	Proportion of silt calculated by adding 4 per cent. of that of surface for each foot below surface.
1	2	3	4	5
0	1st November	3·4	73	73
5			85	85
10			98	97
15			98	109
20			134	134
				Proportion of silt calculated by adding 4 per cent. of that at surface for each foot below surface.
0	6th November	3·47	66	66
5			77	79
10			68	92
15			99	105
20			110	118
25			132	131

Examination of this abstract shows that the law of arithmetical increase of the proportion of silt for each equal increment of depth from surface holds good for all the depths down to 25 and 30 feet. The observed and calculated proportions agree as closely as could be expected. However, the rate of increase varies from 3·7 to 10 per cent. to the foot. It is very remarkable that the two experiments of 20th August exactly agreed with each other, and also with my experiments made eight years previously on the Burraballong, not only in the rate of increase, viz., 10 per cent. for each foot, but actually in the proportions of silt to water. You will remark that Mr. Livesay found from 2 to 2½ times as much silt at the lowest depth to which he went as he did at the surface. You will also see that both a larger proportion and more rapid rate of increase with depth were observed on a rising than on a falling river, but no connection between the quantity of silt and the velocity of the current can be traced, though that such must exist seems reasonable to suppose.

Having now determined the proportion of silt that we may expect to find in a Bengal river, we will see what quantity would probably be deposited each year in the supply channel of the canal we designed at my last lecture.

You will recollect that the surface area was 9,700,000 superficial feet, and that the daily expenditure of water was calculated to cause a lowering of ·2 over this area. The quantity of water consequently that would have to be annually admitted to the canal would be

$$9{,}700{,}000 \times 365 \times 0{\cdot}2 = 708 \text{ millions};$$

but on an average for the whole year for all the Bengal rivers, we obtained 76 of silt to 100,000 of water, so the silting in one year would amount, if the river was an average one, to 538,000 cubic feet.

The truth of this method of arriving at the silting to be expected is proved by the following instance:—

The Kidderpore Docks receive their water from Tolly's Nala, from which it is admitted through a sluice to a canal three miles long, from which it is pumped up into the Docks.

The average quantity of water daily pumped from the canal is 3,000,000 cubic feet, and on the canal there is at present no traffic, and consequently no other source of expenditure of water except the pumping and leakage through lock and sluice estimated at 5 cubic feet per second. The quantity of water admitted annually to the canal is consequently

$$365 \times 3 \text{ millions} + 160 \text{ millions for leakage} = 1{,}255 \text{ millions},$$

10

but the average proportion of silt in the waters of Tolly's Nala was determined to be 69 to 100,000, so the annual deposit should be

$$\frac{1{,}255 \times 69 \text{ millions}}{100{,}000} = 866{,}000 \text{ cubic feet,}$$

or approximately the quantity that we have had annually to dredge out of the canal for some years past.

If it be the case (as I consider I have proved it is) that the proportion of silt increases with the depth from the surface, the question arises—can nothing be done to diminish the proportion in the water admitted to the canal by drawing it from the surface only? With this purpose I placed the sills of the supply sluices of the Coast Canal at as high a level as possible, and the height of each vent was reduced to a minimum, viz., $4\frac{1}{2}$ feet, the width being 5 feet. The upper edge of the vent was placed at the lowest level to which it was calculated the canal would fall. It therefore followed that for a tide which only rose half a foot above the lowest canal level, the supply water would be drawn from the upper stratum 5 feet in thickness. I also placed in front of the sluice pillars with groves for planks, so that for high tides the lower strata might be excluded. However, mature thought and observation have convinced me that the average proportion of silt entering the canal will be the average contained in the water which flows from the river towards the sluice through the short channel connecting it with the river. If the sluice could be put in the river, the case would be different, but to do so is not physically possible. You might construct a great iron aqueduct carried on piles into the river, but the sectional area of the waterway, viz., about 250 superficial feet, would render such an expedient so costly as to be out of the question. Mr. C. E. Livesay has designed and patented a sort of weir for the purpose which he proposes to place in front of the supply sluice, and for an irrigation canal where this weir can be placed right on the edge of the river above the weir there are, in my opinion, possibilities in the device; but if recessed at all, it to a great extent loses its effect, as the eddies produced by the recessing will stir up the water from the bottom, and what goes over his weir will be an average sample of all that enters the recess.

If it were possible to draw from the upper 5 feet, we can calculate the advantage that would be gained over having to take an average of, say, a stratum 15 feet deep from surface.

Let the proportion of silt at surface be 100, then the following table gives the proportion at each depth and the average proportions for the different strata on the assumption that the quantity increases by $\frac{1}{10}$th for each foot in depth :—

		Mean for stratum—	
		5 feet thick.	15 feet thick.
		1	2
At surface	100 ...	...	...
5′ below surface	150 ...	125	...
10′ ditto	200 ...	...	175
15′ ditto	250 ...	...	...

We would therefore get 175 by drawing from a strata 15 feet thick and 125 from one only 5 feet, the advantage of the latter being represented by 50, or 28 per cent. of 175. But we found that the probable silting in one year in the canal would be $5\frac{1}{3}$ lakhs of cubic feet, on which 28 per cent. would be $1\frac{1}{2}$ lakhs, cost of excavating which, say, Rs. 10,000 annually, would represent the saving. If Rs. 1,000 be capitalised at 5 per cent. it amounts to Rs. 20,000. It therefore appears that if a canal be fed from a river carrying on an average 76 cubic

feet of silt to the 100,000 cubic feet of water, it would be worth while to incur an expenditure of Rs. 20,000 to avoid drawing the water from an average depth of 15 feet. However, by placing the vent of the sluice at the level, I have laid down it is not likely that the water admitted to the canal will be an average of 15 feet in depth from the surface of the river.

The next matter we have to consider is the nature of the soil in the alluvial plains of Bengal, in which soil we have to found locks and sluices. Experience has shown that all structures built in these plains sink more or less, and if they sink unequally, cracks and rents appear in the walls. When I first joined the Public Works Department in Calcutta, 26 years ago, several important public buildings were under construction, viz., the Post Office, High Court, and Museum. Serious cracks occurred in all of them, and very shortly after I had joined, I was directed by Major Salisbury Trevor, R.E., then Superintending Engineer, and afterwards Secretary, Government of India, Public Works Department, to calculate the pressures on to the square foot of bearing surface of the several walls of the buildings under construction. I very soon found that the pressures differed much in different parts of the same building which sufficiently accounted for the unequal settlements and consequent cracks in the walls. Since then, all public buildings erected in Calcutta have been designed to have the same pressure on each square foot of their foundations, and the results have been entirely satisfactory.

It is easy in an architectural structure in which the pressures are all vertical to distribute them equally by increasing or diminishing the width of the foundations of the walls according to their weight, but in such a structure as a lock below ground level the problem is greatly complicated by the horizontal pressure exerted against the backs of the chamber walls by the earth filling. In 1881 I had to design the new Chitpore lock, and as all other locks previously constructed within tidal waters had cracked badly, I went into the question very carefully with a view to devising a remedy.

In 1873 Mr. Hugh Leonard, then Chief Engineer of Bengal, had conducted a number of experiments at the Government brick-field at Akra to ascertain the amount of sinkage of the soil under different pressures and at various depths from the surface. He published the results in a note dated 17th May 1873, but the only conclusion he deduced from them was that in Calcutta a greater pressure than one ton per square foot of bearing surface should not be imposed. Now this is a very excellent precept, but unfortunately it cannot be observed in practice except for architectural structures of moderate height. An analysis of the results obtained by Mr. Leonard led me to the conclusion that there was a certain law of sinkage established by them.

Mr. Leonard's experiments were conducted by building brickwork piers founded at four different depths, viz., $2\frac{1}{2}$, 4, 8, and 11 feet from the surface. These piers were 3 feet $2\frac{1}{2}$ inches square, thus giving a bearing surface of 10·24 square feet. They were then loaded, so as to produce a pressure per square foot of bearing surface varying from 1·5 to 3·7 tons, the sinkage produced by the weights being accurately observed. Each pillar was loaded with three different weights, increasing by about a ton per square foot, and they were left with the weight bearing on them in each case until no further sinkage could be observed.

From the results of Mr. Leonard's experiments I have compiled the following table. In it the pressures are shown (in the first column), increasing by tenths from 0 to 4 tons per square foot, and the sinkages observed are shown in inches and decimals in columns 2, 5, 8 and 11. It is at once seen that the sinkage increases more rapidly than the pressure. To try if the sinkage complies with the conditions of a geometric series, take the sinkage observed at (for the foundation $2\frac{1}{2}$ feet deep) 1·2 tons per square foot pressure for the first term of a series of 21 terms and the sinkage observed at 3·2 tons for the last, the ratio will be found to be 1·17. With this ratio the whole series between 1 and 4 tons per square foot is calculated, and it will be seen that the observed middle term agrees with the next term but one as calculated. In the same way if series be calculated for the sinkage observed at the depths 4, 8, and 11 feet, it will be found that the ratios are respectively 1·15, 1·12, and 1·10, and that in two of the series the calculated differs from the observed middle term by only one place, and in the last by one and a half places. It may

fairly be taken as proved that as above stated the sinkages increase geometrically as the pressure increases arithmetically :—

TABLE No. 1.

Pressure in tons per superficial foot bearing surface.	Foundations two and half feet deep.			Foundations four feet deep.			Foundations eight feet deep.			Foundations eleven feet deep.		
	Observed sinkage in inches.	Calculated sinkage in inches; ratio of series 1·17.	Increase of sinkage for each extra 0·1 ton pressure.		Ratio 1·15.			Ratio 1·12.			Ratio 1·10.	
1	2	3	4	5	6	7	8	9	10	11	12	13
1·0		0·22	0·04		0·14	0·02		0·10	0·01		0·60	0·06
1·1		0·26	0·04		0·16	·02		0·11	·01		0·66	0·06
1·2	0·31	0·31	·05	0·19	0·19	·03		0·13	·02		0·73	·07
1·3		0·36	·05		0·22	·03		0·15	·02		0·80	·07
1·4		0·42	·06		0·25	·03		0·17	·02		0·87	·07
1·5		0·50	·08		0·29	·04	0·19	0·19	·02		0·96	·09
1·6		0·59	·09		0·33	·04		0·21	·02	1·06	1·06	·10
1·7		0·68	·09		0·38	·05		0·24	·03		1·16	·10
1·8		0·81	·13		0·44	·06		0·27	·03		1·27	·11
1·9		0·95	·14		0·51	·07		0·30	·03		1·38	·11
2·0		1·12	·17		0·59	·08		0·34	·04		1·53	·15
2·1		1·31	·19		0·68	·09		0·38	·04		1·68	·15
2·2		1·54	·23	0·90	0·78	·10		0·42	·04		1·84	·16
2·3	2·12	1·80	·26		0·90	·12		0·47	·05		2·02	·18
2·4		2·12	·32		1·04	·14		0·52	·05		2·22	·20
2·5		2·50	·38		1·20	·16	0·69	0·58	·06		2·44	·22
2·6		2·93	·43		1·38	·18		0·66	·08		2·68	·24
2·7		3·44	·51		1·59	·21		0·74	·08	3·44	2·92	·24
2·8		4·04	·60		1·84	·25		0·83	·09		3·21	·29
2·9		4·75	·71		2·12	·28		0·92	·09		3·53	·32
3·0		5·57	·82		2·44	·32		1·03	·11		3·87	·34
3·1		6·55	·98		2·81	·37		1·15	·12		4·26	·39
3·2	7·69	7·69	1·14	3·25	3·25	·44		1·28	·13		4·65	·39
3·3		9·02	1·33		3·73	·48		1·43	·15		5·08	·43
3·4		10·60	1·58		4·30	·57		1·61	·18		5·58	·50
3·5		12·45	1·85		4·96	·66	1·81	1·81	·20		6·13	·55
3·6		14·61	2·16		5·71	·75		2·02	·21		6·70	·57
3·7		17·16	2·55		6·57	·86		2·26	·24	7·31	7·31	·61
3·8		20·15	2·99		7·59	1·02		2·53	·27		8·00	·69
3·9		23·65	3·50		8·75	1·16		2·83	·30		8·80	·80
4·0		27·78	3·93		10·08	1·33		3·16	·33		9·67	·87

It is not stated in Mr. Leonard's note what was the nature of the soil found at the various depths at which pillars were built. In order to determine this important point I, with the assistance of Mr. Nightingale, then Executive Engineer, 1st Calcutta Division, searched for and found the experimental pillars at Akra, and had a pit sunk in the midst of them, with the result that all the pillars, except that sunk to 11 feet, were discovered to be founded in light-coloured loamy brick earth, but the latter pillar is built on the bluish-black soil, which is reached at a depth from the surface of a little under 11 feet.

Borings made on the site of the Kidderpore Docks, the subsequent excavations made there during their construction, and borings lately made by Mr. F. V. Taylor at Budge-Budge when getting up a project for a railway tunnel under the Hooghly, show the general character of the alluvial strata to be as follows :—

For about 10 feet from the surface loamy soil and then for a further depth of about 50 feet the characteristic bluish-black clay interspersed with timber in a peaty condition and occasionally nodular limestone. Below the clay occurs water-bearing sand, and old borings made in Fort William to a depth of about 350 feet showed a constant succession of layers of sand and clay. The alluvial crust has never been got to the bottom of. Your Professor, Mr. Gilliland, has

of late been investigating the problem of the compressibility of this alluvial soil by the light of mathematics and physical science, and I look forward to a note by him on the subject of great value. I understand that, as far as he has gone, he has reason to believe that the empirical law deduced by me may be confirmed by analysis.

Applying the law of sinkage which I have enunciated to the cases of the various tidal locks built in Bengal previous to 1881, I showed that the width of the cracks which had occurred in their sills agreed with the width calculated by the application of this law. Chitpore lock designed by its light settled exactly as was expected, and since then the locks on the Coast Canal designed by me have been very satisfactory. Further, its truth has been shown by the observed sinkages of the walls of the Kidderpore Docks, where they unfortunataly moved, and also by those of the walls and towers of the High Court.

In the case of the Dock walls it was observed that those of the tidal basin when backed on both sides and pressing evenly on the subjacent soil with an intensity of 2·3 tons per square foot sank 3 inches, and the maximum pressure at the outer toe of the wall which moved was calculated to have been 4·2.

Now 4·2 is the 20th term of an arithmetical series, of which 2·3 is the first term, and 0·1 the common difference. The corresponding geometrical series giving the sinkage will have 3 for its first term, advancing to the 20th by the common ratio 1·1 determined from Mr. Leonard's experiments for the black clay. The 20th term of sinkage due to 4·2 tons per square foot will therefore be $3 \times 1{\cdot}1^{19} = 18{\cdot}34$ inches, but the actual sinkage was 16·2 inches corresponding to a pressure of 4·07, or only 0·13 less than that calculated.

In 1892 I was asked by the Government of Bengal to advise what measures had best be adopted to arrest the forward inclination of the south wall and tower of the High Court. I found that the main building had settled 6·47 inches, the pressure being 1·54 tons per square foot of foundation, but the tower had settled 16·19 inches, the pressure per square foot being 2·38 tons. In an arithmetical series of which 1·54 is the first term and 0·1 the common difference, 2·38 will be the 9·4th term, and in the corresponding geometrical series for the sinkages the ratio will be 1·115, which closely agrees with that, viz., 1·12 deduced from the Akra experiments for foundations of about the same depth.

The practical lesson taught by the apparent law of sinkage, the evidence in favour of which I have been laying before you, is that we must be careful to get our pressures as equal as possible, as a very slight difference in the pressure may make a very large one in the sinkage.

As I have already remarked, you can distribute the pressures on the foundations of a house with mathematical accuracy as the forces in operation, viz., the weights of the different portions of the strucure are vertical. In a canal lock such is not the case, as the pressure of the earth filling on the back of the wall causes the position of the weight and earth pressure of the vertical resultant to vary, and this earth pressure cannot be ascertained with accuracy. In the design of the canal lock before you, which was that adopted for the Orissa Coast Canal, the centre of gravity of the half lock, including half the floor, is immediately over the centre of bearing surface, that is, half way between the centre of floor and the back of the wall. The pressure of the earth also passes through the centre of the bearing surface when the angle of repose is taken at 2 to 1. Backing of the kind to be obtained within tidal limits is likely to have a natural angle greater than 2 to 1, in which case the resultant of the earth pressure and the weight will cut the bearing surface nearer to the centre of the lock than the back of the wall, but settlement towards the centre will be resisted by the strength of the floor in compression. On the other hand, if the resultant be behind the centre of bearing surface, the tendency will be for the lock walls to settle backwards, which is only resisted by the tenacity of the floor which is small. All the tidal locks built previously to those on the Coast Canal did settle backwards, causing crack through sills, but the Coast Canal locks have been entirely successful. With regard to the use of inverts to distribute the pressure, I would point out that 20 feet is the limit of width of a lock in which a brick-built invert can distribute the pressure, as with a greater width the limit of resistance of bricks to crushing is reached in the arch of the invert. In the Coast Canal locks the inverts were

built, not in separate rings, but bonded through, and then they were filled into a level floor in order to gain weight which was required to bring the centre of gravity of the half lock over the centre of the bearing surface. In a lock 40 feet in width the weight cannot be distributed by an invert, and if it could be, it would tend to tilt back the walls. The expedient I have adopted in such cases is to put a straight joint in the floor parallel to the face of the wall, and as far from it as the floor is thick. When the walls and the detached centre portion of the floor have finally settled, then the straight joint is built over for the upper foot or two of the flooring. This method adopted at the Kidderpore Docks was quite successful.

Another point to attend to is the designing a lock, so that as nearly as possible the walls shall have the same section from end to end. The through tunnel with small vents into the lock chamber for filling and emptying is the best arrangement, as water is admitted to the lock chamber gently without causing any surging. It is much cheaper and better to join the locks to the embankments by dry revetments than by wing walls which revetments can be made of brick or concrete blocks if stone is not available.

In tidal waters iron corrodes with great rapidity, and consequently iron gates are shortlived. Timber unfortunately is attacked by the teredo. But on the whole I prefer soild wooden gates of well-seasoned teak sheated with copper or yellow metal such as were used on the Coast Canal to those made of iron.

The illustration of a supply sluice which I give needs but little description beyond that already given. It is provided with a flap shutter on the canal side which closes when the river level falls below that of the canal and so impounds the water in the latter. It also has draw shutters for regulating the admission of water to the canal.

With a few words on foundations, concrete and brickwork, I shall conclude this lecture.

The blue-black clay I have already spoken of in which you will have to found your locks is extremely treacherous. An excavation in it with almost vertical sides may stand for a considerable time, but the sides will be liable to collapse at any moment, and if they do, the average slope they will subsequently assume will be often as flat as $7\frac{1}{2}$ to 1. The steepest that it is at all prudent to make the slopes of a foundation pit is 3 to 1, and even with this slope it is about even chances that they slip, wrecking the foundations that you may be getting in. In the Kidderpore Docks about half the 3 to 1 banks in the open cuttings did so slip, and I had similar experience in locks on the Coast Canal. You should only open a small area at a time in which as quickly as possible get in your foundations. Do this in disconnected pieces all over the site, and then by degrees excavate between them, and so eventually you get in your brickwork over the whole area. If the depth of foundations exceeds 25 feet from the surface, it will be advisable to build them in timbered trenches of small width. Piling as a means of improving the bearing of this soil is, for reasons that I cannot now afford time to go into, worse than useless, and should never be attempted.

My advice with regard to concrete is not to use it in foundations where there is any danger of slips occurring, which danger will be greatly increased by the vibration caused by the ramming of the concrete. In a doubtful foundation put brickwork which can be got in quicker and much more quietly than concrete, and it also has the advantage that its strength even before the mortar is set is considerable, whereas concrete has no strength whatever until the mortar has hardened and in more instances than suspected it never sets at all. Especially when you make your own bricks you will have lots of broken stuff to work up, and my practice has been to put this into the superstructure when I have got in my foundations safely. Concrete is a most excellent material when well made, but to break up whole bricks (as I have often seen done) with the intention of again sticking the pieces together never seemed to me a wise thing to do. In Europe ballast is frequently dug out of the foundation pits, which with a sufficiency of cement makes the most excellent concrete, but in Bengal it can only make it of broken bricks, and I would in preference use them whole. On the Orissa Coast Canal in one place when no brick earth was available, but nodular limestone (ghooting) was

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DIAGRAM SHOWING HIGHEST (NIGHT) TIDE EACH 24 HOURS FOR LOWEST TIDES OF YEAR AT DIAMOND HARBOUR

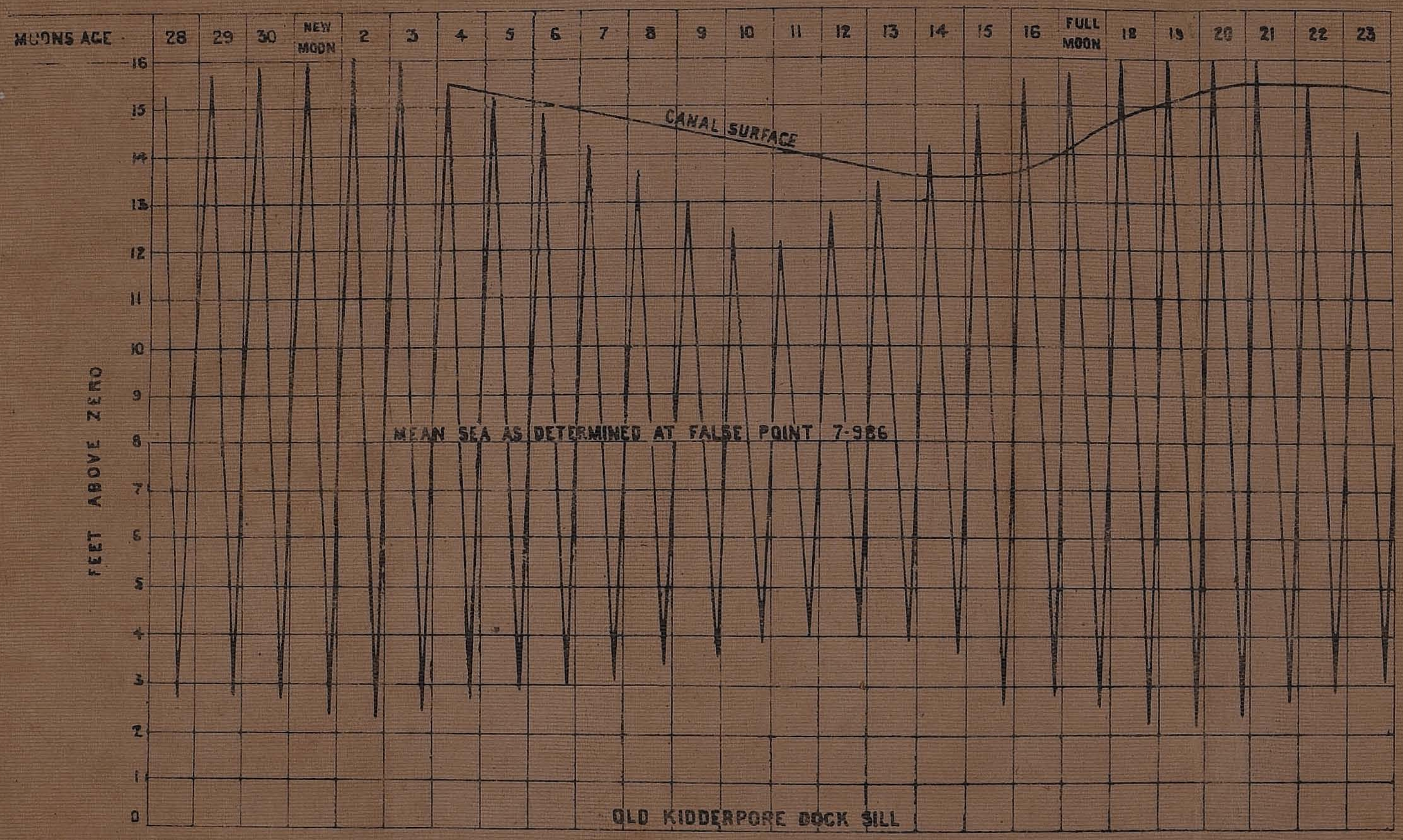


DIAGRAM No 1

DIAMOND HARBOUR
TIDAL CURVE
FOR
HIGHEST TIDE
IN
DECEMBER

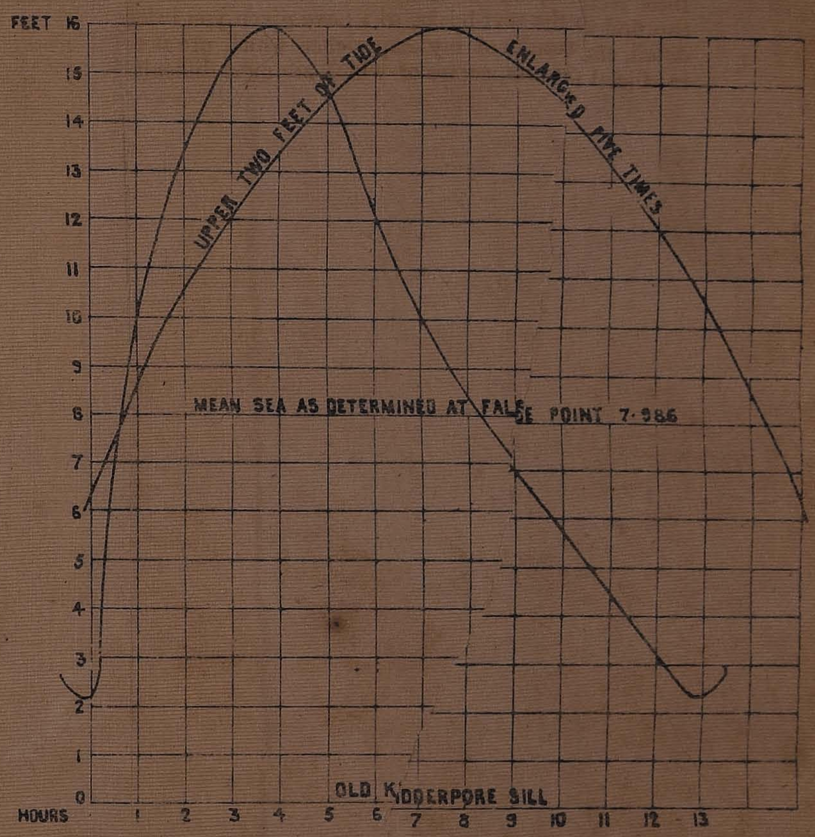


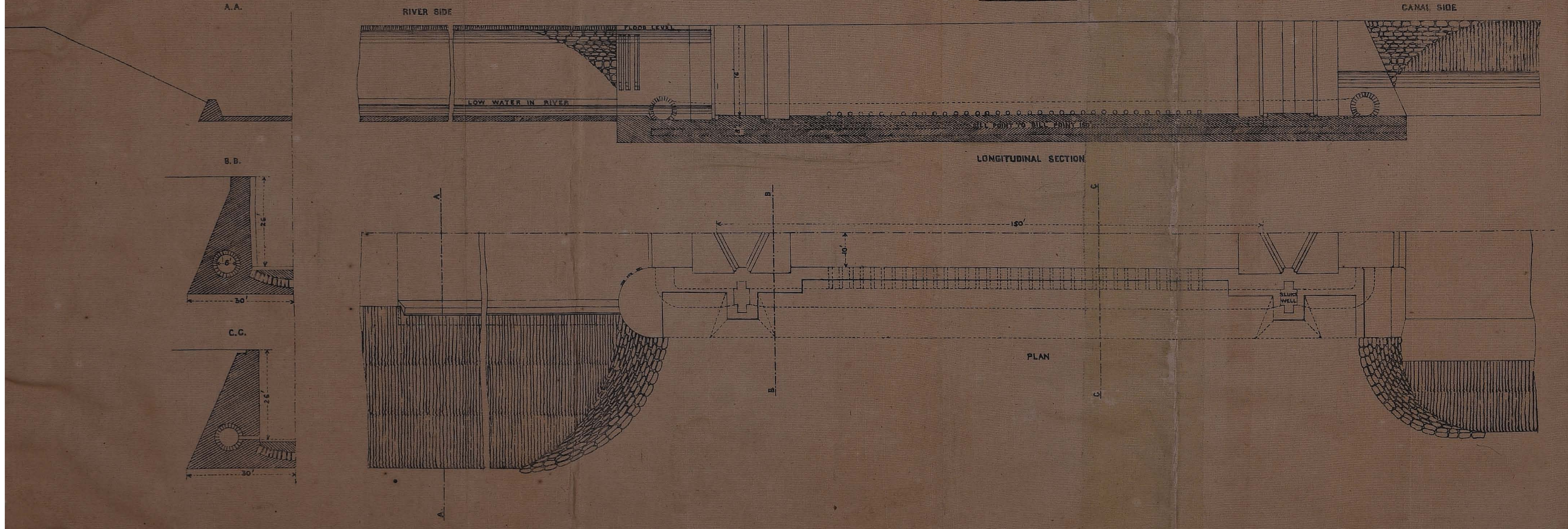
DIAGRAM No 2

D 2.254.S
M95

15 16 17

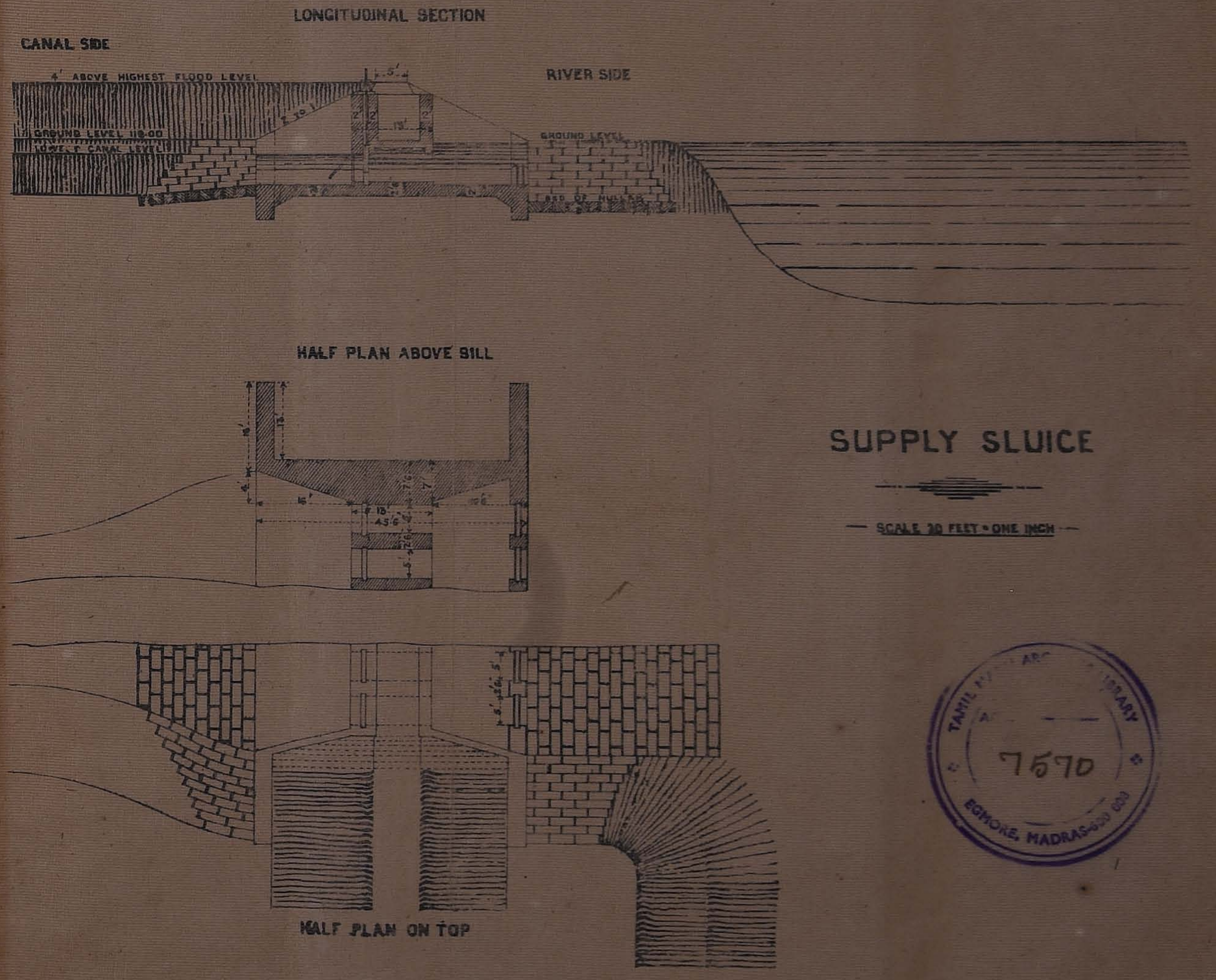
TIDAL LOCK

SCALE 20 FEET = ONE INCH



SUPPLY SLUICE

SCALE 20 FEET = ONE INCH



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abundant, I built two sluices with concrete made from the nodular limestone, but I hear that they have weathered a good deal on the faces of the walls in the ten years that have elapsed since they were built.

In brickwork I would impress on you the immense importance in hydraulic works of securing a thorough filling of the joints with mortar. It is extremly difficult to get the Bengali bricklayer to fill the vertical joints, and if he does not do so the wall will never be watertight. In all brickwork subject to a head or rapid current of water such as a lock sill or sluice floor, avoid the usual horizontal courses with no bond between them. In such cases every course should bond with that above and below it, and I cannot better describe this method of construction than by saying that the bricks should lie as they would in a wall built in courses with old English bond and then laid on its side. A sluice floor so built will resist successfully any current of water, and I should prefer it to a floor covered with blocks of ashlar unless the stones bonded with those below.

Gentlemen, I fear that the first person singular has been used too often in these lectures, but there was no need for me to talk to you about what you can find in the text-books, so I have given you briefly, but I trust in sufficient detail, the results of my experience which are not otherwise available except in official reports, copies of which are most difficult to obtain.

E. J. H.—Reg. No. 378J—500—22-5-95.